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A comprehensive review of variable renewable energy levelized cost of electricity

Wei Shen [a,*], Xi Chen [a], Jing Qiu [b], Jennifer A Hayward [c], Saad Sayeef [c], Peter Osman [c], Ke Meng [a], Zhao Yang Dong [a]

[a] School of Electrical Engineering and Telecommunications, Sydney, University of New South Wales, Australia
[b] School of Electrical and Information Engineering, University of Sydney, Sydney, Australia
[c] CSIRO Energy Centre, CSIRO, Newcastle, Australia

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ABSTRACT

Levelized cost of electricity (LCOE) is widely used to compare the cost of different electricity generation technologies. However, with the increasing penetration of variable renewable energy (VRE), it is inappropriate to use traditional equations to calculate the LCOE for non-dispatchable VRE due to its intermittent nature. Therefore, this paper reviews LCOE for renewable generation considering aspects such as improving traditional methods for evaluating and reducing the LCOE of VRE. The existing methods for improving the accuracy of the traditional LCOE have been divided into four aspects: investment-related cost, operating-related cost, expressions for plant performance and the uncertainty and risk-related costs. The review summarizes the existing studies from academic articles and technical reports and proposes suggestions for future research studies.

1. Introduction

Variable renewable energy (VRE) plays an important role as a low-carbon technology in solving climate change. The installed capacity of VRE has increased significantly in recent years. For example in Australia, the cumulative installed capacity of wind energy increased from 1840.1 megawatt (MW) in 2010–6279.4 MW in 2019 [1]. More than 2.2 GW of new large-scale renewable energy was connected to the power grid in 2019 and renewable energy represents 24% of Australia's electricity generation [1]. The penetration of VRE will continue increasing in future electricity generation systems. In order to compare the cost between different types of generation technologies a levelized cost of electricity (LCOE) is defined and it is commonly accepted as the metric for economic analysis of power generation systems [2]. This method estimates the average total cost of constructing and operating an electricity generation asset over its entire plant life divided by the total power output of the asset over that lifetime.

LCOE is widely used among researchers, investors, project managers, and policy makers. For example, by comparing the LCOE with the market electricity price, investors and project managers can assess the competitiveness of different technologies and make decisions on whether to invest in renewable energy projects by using the LCOE to determine the market price for which an investment in power generation is profitable [3,4]. Furthermore, policy makers could set renewable energy policies with the assistance of LCOE values. Considering the existing policies that influence LCOE calculation can offer a reference for policy makers to set future incentive policies [5]. Although LCOE results can be used for these applications, the calculation of VRE LCOE introduces new challenges compared to traditional LCOE methods. These include: 1. VRE LCOE is location specific and this together with the nature of the renewable resources, will influence the capacity factor and the capital and O&M costs. 2. VRE LCOE input variables may be interdependent. 3. Plant-level LCOE calculation is not enough to determine the cost as the intermittency of VRE can increase grid related costs. 4. There is more uncertainty and risk in estimating VRE LCOE due to its intermittency. 5. VRE LCOE is susceptible to renewable policies and harmonisation issues.

To date researchers have modified traditional LCOE methods to improve their accuracy based on the above challenges. Studies [2,6–15] discuss the impact of location on LCOE and propose using a geographically-based method, LCOE mapping, to improve the accuracy of LCOE results. The relationships between LCOE input parameters are presented in Ref. [15,16]. Several system-level LCOE methods are proposed in Ref. [17–33], including system-adjusted LCOE, levelized

* Corresponding author.
E-mail address: wei.shen@student.unsw.edu.au (W. Shen).

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avoided cost of electricity (LACE) and marginal system LCOE. Scenario-based methods, sensitivity analysis and probabilistic methods are proposed in Ref. [2,6,7,11,16,29,30,34–42] to solve the uncertainty and risk issues. Subsidies and carbon policies in LCOE calculation are discussed in Ref. [2,5,13,34,36,39,43–47]. A harmonized method [48] is proposed to compare the input data of different LCOE studies on a common basis. In Ref. [49], a novel levelized cost of consumed electricity is proposed considering location-specific behavior, solar irradiation uncertainty, variations in tariff rates, and the additional cost of using smart grid equipment. Temporal variation in market prices are considered in Ref. [50] as well as transmission capacity constraints.

Previous LCOE review studies have also been carried out [30,51–54]. In Ref. [30], the LCOE of solar photovoltaic (PV) has been reviewed and the authors mention that in LCOE calculations, the lack of clarity in assumptions and justifications could generate misleading results. Cost metrics including LCOE, undiscounted cost of energy and the total cost of energy are reviewed and compared in Refs. [51]. In Ref. [52], the LCOE of recent reports has been reviewed and the LCOE of geothermal energy techniques are calculated and compared with other technologies. The LCOE for marine energy has been reviewed in Refs. [53]. In Ref. [54], the authors demonstrate that the traditional LCOE metric is inappropriate for comparing dispatchable generation with VRE. This paper gives a comprehensive review of LCOE which assesses the existing LCOE method, discusses potential methods to improve the accuracy of VRE LCOE results, lists the LCOE reduction methods, summaries the existing LCOE results for different technologies, and makes recommendations to guide future research directions.

The structure of this paper is organized in Fig. 1. The overview of existing LCOE methods are reviewed in Section 2 including the LCOE annuitizing method and the LCOE discounting method. The summary of VRE LCOE calculation major inputs can be found in Table 1. In Section, the traditional LCOE evaluation methods are assessed from four different aspects including investment-related cost, operating-related cost, the expression of plant performance and uncertainty and risk-related cost. The summary of traditional LCOE calculation parameters and elements should be considered can be found in Fig. 2. The existing methods for improving the accuracy of LCOE estimates are discussed in Section 4 based on the four aspects discussed in Section 3. Methods for reducing the value of LCOE of VRE are shown in Section 5 including total cost reduction and increasing energy production. Two large tables listed in Section 6 summarize the existing LCOE study in academic papers and technical reports considering the LCOE inputs, LCOE range, contribution and findings. In Section 7, the conclusions, future work directions and recommendations are presented.

2. LCOE overview

The LCOE indicates the unit costs of electricity over the full life or economic life of a project and it is widely used to measure the feasibility and competitiveness compared to other technologies [51]. In general, LCOE is calculated by the lifecycle costs of the system (in $) divided by the lifetime electricity production (in kWh) as shown in equation (1)

$$\mathrm{LCOE} = \frac{\text{Lifecycle cost}}{\text{Lifetime electricity production}} \quad \left(\$/\mathrm{kWh}\right) \tag{1}$$

Two major LCOE methods are widely used, known as the "annuitizing" method and the "discounting" method. These were suggested by the United States (US) Department of Energy's National Renewable Energy Laboratory (NREL) and the UK Department of Business, Energy and Industrial Strategy (BEIS), respectively.

2.1. LCOE annuitizing method

The LCOE method suggested by NREL mainly considers the issue of capital recovery as shown in equation (2) [51,55]:

$$LCOE_{annuitizing} = \frac{C_{on} \times \overbrace{\left[i \times (1+i)^n / (1+i)^n - 1\right]}^{\text{capital recovery factor}}}{8760 \times \sigma} + V \tag{2}$$

where C_{on} refers to the overnight capital cost (in $/kW); i and n represent the interest rate and the number of payments made to repay capital; σ is the capacity factor and V(in $/kWh) is the variable operation cost; the expression in square brackets refers to the capital recovery factor (CRF).

There are two parts in $LCOE_{annuitizing}$, annualized capital cost and annual variable cost. Annualized capital cost can be obtained using the overnight capital cost divided by the energy production over any year and corrected with the CRF. The annual variable cost is then added to produce an LCOE in $/kWh.

2.2. LCOE discounting method

The LCOE indicator used by BEIS takes into account the cost and depreciation of the entire project life cycle, resulting in the lifetime cost of energy as shown in equation (3) [51]:

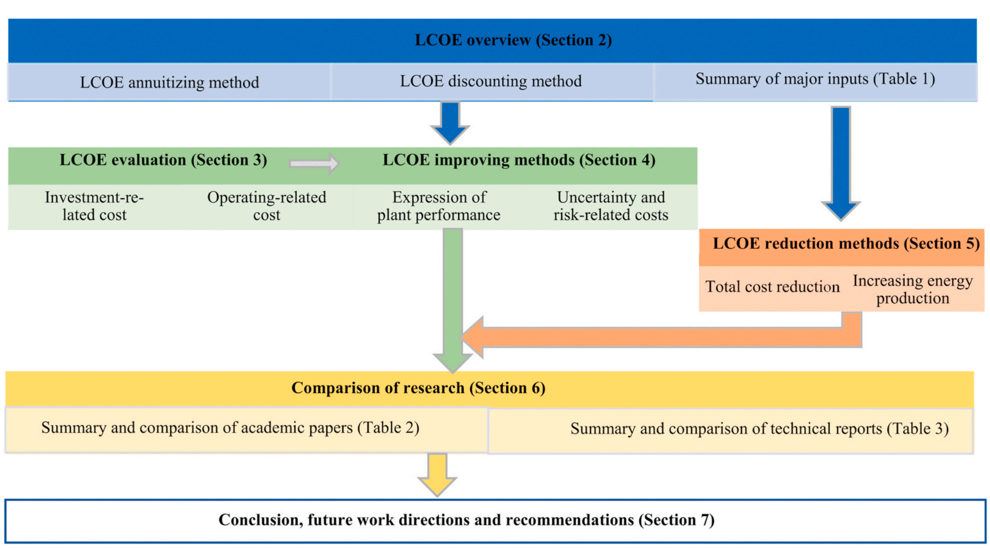

Fig. 1. Outline of key points in LCOE review paper.

Table 1
Summary of major inputs for VRE LCOE calculation.

Major input variables	Explanation	Impact to LCOE
Capital cost	The capital cost for VRE represents a large proportion of the total project lifetime cost [2]. The capital cost for VRE projects could include the cost of structure, foundations, control systems, turbine installation cost, etc. The capital cost is influenced by the type of technology, project lifetime, system size and geographical location [2].	If other input variables are the same, the higher capital cost can lead to higher LCOE results.
Operations and maintenance (O&M) cost	The O&M cost refers to the annual cost associated with VRE generators' operation and maintenance. For conventional thermal power plant, fuel costs represent a large portion of O&M cost, however fuel costs are zero for VREs. The O&M cost for VRE projects could include the cost related to planned maintenance, monitoring, control, unscheduled repair, power export related cost, etc. Compared to traditional coal-fired plants, the O&M cost of VRE such as wind and solar is usually smaller as they require less maintenance [2]. System scale can affect O&M cost. The O&M cost is affected by the type of technology, system scale and geographical location.	If other input variables are the same, the higher O&M cost can lead to higher LCOE results.
Energy performance (Capacity factor)	Energy performance is the conversion of renewable resources into energy from a particular technology [2]. The nameplate capacity of renewable power plant and the capacity factor are usually used to calculate energy production. The average capacity factor of any type of existing generation technology can be calculated, but it is difficult to assess the emerging technologies due to the lack of data. Furthermore, information on the dispatchability and reliability of a power plant is built into the capacity factor [8]. The energy performance (capacity factor) is critically dependent on both the generator rated annual energy production and its average annual energy production. These are both impacted by the type of technology, renewable resources, weather condition and electricity grid constraints (power export capacity).	If other input variables are the same, the higher energy performance (capacity factor) can lead to lower LCOE results.
Lifetime	Project lifetime is the total time that an energy system is available to produce electricity. The life of a project directly affects the capital cost. An energy system with a longer service life can provide more economic benefits [8]. However, lifetime is generally an estimated value, and life cycle uncertainty may result in a larger range of LCOE values. The project lifetime is impacted by the technology, operation condition, and location.	If other input variables are the same, the higher lifetime can lead to lower LCOE results.
Discount rate/ interest rate	Normally, VRE projects, such as wind and solar farm can operate more than 20 years. Therefore, it is important to consider the time value of money. The future cash flow value in the present can be obtained using a discount rate [56,57]. The discount rate varies by location, circumstance and the time period [30].	If other input variables are the same, the higher discount rate can lead to higher LCOE results.
Degradation rate	Similar to the concept of the discount rate, the future annual energy output will be decreased. The degradation rate is defined to show the decrease of plant efficiency with increasing age. The degradation rate can be influenced by the technology, operation environment, location, and the age of the project.	If other input variables are the same, the higher degradation rate can lead to higher LCOE results.

$$LCOE_{discounting} = \frac{\sum_{t=1}^{T}(CAPEX_t + OPEX_t + V_t) \Big/ (1+d)_t}{\sum_{t=1}^{T} E_t/(1+d)^t} \tag{3}$$

where $CAPEX_t$(in \$) and $OPEX_t$ (in \$) are the capital and operation cost in period t, respectively; V_t refers to the variable cost (in \$) in period t such as carbon costs, and taxes, etc.; E_t represents the electricity generated (in kWh) in period t; d is the discount rate and T is the total operation period (in years).

$LCOE_{discounting}$ reveals the energy price (in \$/kWh) and is calculated by dividing the discounted sum of costs by the discounted sum of energy production.

2.3. Comparison of annuitizing method and discounting method

The values of $LCOE_{annuitizing}$ and $LCOE_{discounting}$ are exactly the same once the following conditions have been met: 1. The annual output value and cost of the project are constant; 2. All construction expenditures occur in the first year; 3. The financing term is made equal to the project operating life; 4. There is no decommissioning expenditure [51].

$LCOE_{annuitizing}$ and $LCOE_{discounting}$ are simple but incomplete methods. They both estimate the relative cost of energy, but it is crucial to users to ensure that the cost indicators they include or exclude are consistent with the coefficients in the formula [51].

2.4. Summary of typical VRE LCOE inputs

There are several inputs required to calculate the LCOE of VRE and the major inputs are listed below:

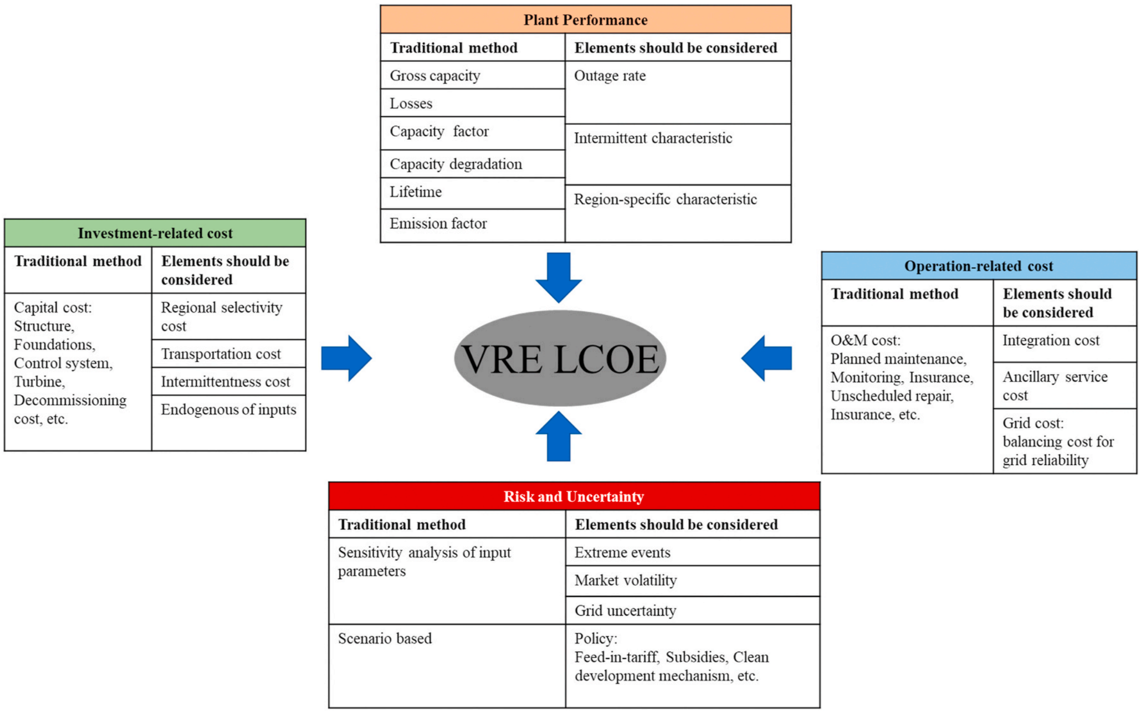

Fig. 2. LCOE evaluation.

3. LCOE evaluation

LCOE evaluation has been developed to compare dispatchable, baseload generation technologies [3,58]. The traditional LCOE methodology is not suitable for non-dispatchable intermittent VRE. Traditional LCOE calculation parameters are listed in Fig. 2 as well as the elements that should be considered to improve the accuracy of VRE LCOE calculation due to its intermittent nature. These elements can be divided into four aspects:

- **investment-related cost**
- **operating-related cost**
- **expression of plant performance**
- **uncertainty and risk-related costs**

For investment-related costing, considering the additional cost brought by regional selectivity can be more accurate, as energy resources and economic data for different location are different [6–8]. Studies [2,6–8] indicate that the construction and operating cost of identical plants across different geographies will be different and not every type of power plant can be built in every location. For example, the capital cost for wind farm are ranging from 1629 ($/kW) to 2180 ($/kW) at different locations of the United States [7]. In Refs. [16] the authors point out that endogeneities between inputs are ignored, such as the CAPEX and lifespan, CAPEX and OPEX, etc. As for the operation-related costs, the following aspects should be considered in VRE LCOE calculation, including the integration cost of energy [6,17,42,59], reasonable ancillary services and balancing costs to achieve grid stability and reliability [18,28,42,59,60] and grid cost [17]. Traditional LCOE cannot show the impacts on the system after connection, ignoring variability and integration costs as proposed in Refs. [6,17,61], and this issue could be more severe in the future with the possibility of high VRE market penetration which would require more balancing system reserve capacity to satisfy system reliability [18]. There will be a range of generation technologies required for future VRE generation systems. Therefore, VRE LCOE needs to consider the electricity systems and the interaction between other electricity generation technologies [42,59]. High penetration of VRE generation in electricity systems can lead to grid stability and reliability issues and the transmission congestion can be more frequent. Hence, VRE LCOEs calculations will need to consider the potential additional costs from ancillary services for grid stability and reliability [18,60] as well as transmission line congestion-related grid costs [17]. The effects of energy delivery limits on VRE which will be imposed by Power Purchase Agreements (PPA) should be included in the LCOE calculation, as PPA can change the energy delivery limits and impact the LCOE correspondingly [43].

The expression in plant performance focuses on capacity factor assumptions. In the literature, capacity factors are usually set as constant over the plant lifetime, which is not the case for VRE technologies [7]. For example, the reliability and dispatchability of the generation technology affects the capacity factor [2]. Therefore, the capacity factor requires a complex calculation instead of a simple assumption. Furthermore, the capacity factor should be region-specific since renewable resources are geographically dependent and this is rarely considered in the existing studies. VRE systems often comprise groups of generators and this requires considering the way the generators interact with each other. Normally, there are several turbines in a wind farm or tidal farm which can cause wake effect. Wake effect represents the aggregated impact on energy production that results from the changes in wind speed caused by individual turbines. When grouped together some turbines will tend to change the wind velocity that acts on neighbouring turbines [62]. For example, it is also necessary to consider the wake effect in wind or tidal LCOE calculations as the layout of the wind or tidal turbines can change the total energy production and change the LCOE results correspondingly [15].

To calculate LCOE more accurately, the uncertainty and risk-related cost are indispensable elements, especially for VRE as inherent intermittency is not easily predicted [2]. These elements can be summarized as uncertainties of input parameters [11,60], additional costs caused by market volatility [6,60,63], policy uncertainty and the impact of extreme events [60]. Generally, traditional LCOE ignores uncertainties by using point values for all input parameters such as constant capacity factor, constant discount rate, etc. which could cause misleading results [11,60]. For example, in Ref. [11], after considering the uncertainties, the LCOE distribution are generated with the LCOE value and probability which is easier for investor to make decision. It is necessary to consider the uncertainties in projecting future LCOE values [7]. Policies related to VRE could decrease the LCOE and make it competitive with conventional coal or gas plant. These policies are rarely considered in existing studies and the future policies on VRE are unpredictable. Last but not the least; The calculation of LCOE ignores the issues of economic resilience to extreme events such as fuel spikes, storms, etc. [60].

4. Existing methods for improving the accuracy of LCOE results

The elements discussed in Section 3 can improve the accuracy of LCOE results. This section summarizes the existing methods reported in the literature for improving the accuracy of LCOE estimates.

4.1. Investment-related cost

4.1.1. Location based

In the literature, most academic papers and technical reports calculated LCOE at a national level. National-level LCOE using average values for the calculation is appropriate for long-term energy planning and energy policy making. However, it is inappropriate to use average LCOE for analyzing specific VRE power plant as the LCOE of VRE varies by project, country and technology [9,10]. LCOE being used for analysis is reflective of the case being investigated. In particular the meteorological data for different locations is most significant in determining renewable resources and power plant capacity factor. Likewise, the capital cost and O&M cost for the same technology can also vary greatly with regional differences in generation installation cost, equipment freight cost and labor wages. Therefore, the plant location can significantly impact the VRE LCOE results for any given technology. For a specific project with location information, traditional LCOE can be improved by considering real time market price [60], time or seasonally dependent electricity pricing as well as the full net present value (NPV) of an investment [6, 48,63]. In Ref. [11], the effect of location on the uncertainty in renewable energy LCOE is discussed. The results show that the locations can shift LCOE values by around 50% amounts and the uncertainty of LCOE decrease for favorable location [11].

In [12], an LCOE mapping method has been proposed to consider the site specific capital cost, operational cost and technical specifications. The LCOE mapping shows the LCOE in a specific region and it is easy to find the zones restricted to a certain value of LCOE. Moreover, by using this method, the optimal location of renewable power plants can be found. Similarly, in Refs. [6] a geographically-solved method has been proposed, which calculates the LCOE on a country-by-country basis. The minimum LCOE technologies for each location is found based on local characteristics such as, local capital costs, local environmental externalities and local resource availability. In Ref. [13], the LCOE of solar PV has been mapped globally. The location-specific parameters include the regional cost difference, country-specific discount rate, cost, and policy risk. Location-based cost adjustment factors considering different living cost levels and remote location-related costs are proposed to calculate the capital cost in different locations in Ref. [14]. The cost in remote location such as seismic design, larbor wages and productivity differences are solved using the cost adjustment. In Ref. [15], a land-based LCOE has been proposed considering the following differences: equipment suppliers, construction contractors, overheads, profit requirements, plant performance guarantees, the use of union or non-union labor, sales tax rates, access roads, laydown areas, transportation distances to site, availability of utility and indoor or outdoor buildings, ambient temperatures, and many other site-specific issues affecting scope and specific equipment needs and choices. In Ref. [7], the data for CAPEX and O&M are region-specific and the authors also developed the map-based LCOE calculator with regional multipliers.

In real cases, additional cost needs to be taken into account to improve the accuracy of LCOE results. In Ref. [64], social acceptance costs are considered in a LCOE calculation. Social acceptance costs may for example include compensation costs, project development costs associated to local resistance such as the property value loss due to the construction or operation of the VRE plants [64].

4.1.2. Relationships between inputs

In the literature, the relationships between LCOE input variables are assumed to have no correlation. The changing of one input variable cannot impact other input variables. However, in reality, LCOE inputs may be interdependent, especially for the calculation of VRE LCOE. For example, O&M cost and energy production (capacity factor) may be correlated, as the generation outage rates can impact both O&M cost and energy production. In Ref. [15], researchers find that in existing studies, it is unclear and there are no indicators to estimate if innovation related CAPEX is directly linked to OPEX or decommissioning costs. To resolve this issue, sort analysis has been applied in Ref. [15] to understand the relationships between different input parameters. The sorting method is able to find the variation in variables given the behavior of other variables [15]. The CAPEX, OPEX, LCOE, net energy production, and weighted average cost of capital (WACC) for 98 scenarios have been normalised and sorted. However, the authors fail to draw robust conclusions on the relationships between the above parameters by using sort analysis. The authors suggest using statistical methods or optimization techniques to establish the relationship between input variables. A statistical method, Spearman's rank-order correlation is applied in Ref. [16] to simulate correlations between variables. This method requires a monotonic relationship between the variables. This study illustrates that the mean LCOE estimate is 1.5% higher when the input correlation is included [16].

4.2. Operational-related costs

4.2.1. System LCOE

The traditional LCOE equation as a common metric only considers the plant level cost which makes it possible to compare with previous studies and other technologies. However, the plant level estimation cannot cover all costs from the newly built plant, especially for VRE. This is because the power output of VRE is difficult to predict, and hence could lead to system reliability issues and it needs support from the grid. For example, the sudden drop of renewable generation could lead to a lack of power supply which needs compensation from other generators in the system. Therefore, LCOE for renewable energy with just the plant level cost is insufficient. System level costs are often divided into four categories: profile costs, costs of balancing, grid costs and costs of connection [17,65]. The profile costs can include the overproduction costs, full-load hour reduction costs and backup costs [17].

In the literature, a system LCOE is proposed in Ref. [17] which includes the costs of variability on a system level. System LCOE includes plant level cost and the costs of integration. The integration costs refer to the costs accommodating VRE, including balancing costs such as forecast error related cost, grid cost such as line congestion management cost, adequacy cost such as backup cost and flexibility cost such as ramping cost [17]. In Ref. [18], seven published studies have been reviewed that take into account the balancing cost in LCOE [19], including ITP study for ARENA which proposes a calculation method for considering the storage capacity [20]; the MEGS report [21]; Levelized avoided cost of electricity which estimates the diversity and flexibility in energy provision [22]; CSIRO electricity system modelling which the balancing solutions including battery, hydro storage and conventional synchronous generation are considered [23]; National Electricity Market Optimizer which calculates the levelized cost of generation and levelized cost of balancing [24–27]; Power system generation mix model which estimates the LCOE from a system perspective [65]; IEA's Value adjusted LCOE which considers the differences in value each technology provides to the power system [19]. The LCOE model is extended in Refs. [28] and the cost of supported VRE to ensure reliability are provided.

The supported VRE includes the following aspects: existing flexible generation types and capacity, demand management; the share of VRE, the diversity of VRE, the type of energy storage system, and the reliability standards [28]. When comparing LCOE studies, it should be made clear if they incorporate reliability considerations to ensure a more realistic assessment.

4.2.2. Marginal system LCOE

In [29], the marginal system LCOE has been proposed. For VRE, the marginal system LCOE refers to the change in system cost divided by the change in energy production caused by a change in VRE market penetration [29]. The authors conclude that with the increase of VRE penetration, the system LCOE should increase correspondingly. Once VRE penetration is above 80%, the system LCOE increased sharply [29].

4.2.3. Levelized avoided cost of electricity (LACE)

LACE (in the units of \$/MWh) measures the plant value to the grid [32]. This avoided cost is the potential cost to provide the electricity displaced by a new electricity generation project [30–32]. This is a weighted average cost of the marginal cost of electricity dispatch. LACE is calculated in equation (4)

$$LACE = \frac{\sum_{t=1}^{T}(C_{P,t} \times H_t) + (C_R \times \delta)}{E_h} \tag{4}$$

where $C_{P,t}$and C_R refer to the marginal generation price (in \$) at time t and the capacity payment to the electricity system of satisfying the system reliability margin (in \$), respectively;H_t and E_h are the dispatched hours and the annual expected generation hour in a year; δ is the capacity credit which represents the capability of the generating unit to provide power reserves and Trepresents the number of time periods in a year [22].

This LACE is the potential revenue from a candidate project displacing another marginal asset. The avoided cost considers the variation in demand (daily and seasonal) and regional existing generation mix, etc. [33]. Moreover, LACE can incorporate performance factors [6]. The relative difference between LCOE and LACE is an economic competitiveness indicator which measures how attractive the technology is to replace existing plant while satisfying the demand and supply balance [18,33]. If multiple technologies can supply the regional power demand, this indicator can be used to decide between them by calculating the highest net economic value [33]. The difference between LACE and LCOE will vary by technologies and regions. If the value of LACE is higher than the LOCE, the plants are considered economically attractive, as LACE can be seen as revenues and the LCOE are payments [33].

4.3. Plant performance

VRE power plant performance can vary significantly at different locations for the same technology due to the differences of renewable resources. For example in Australia, the average wind speed in coastal areas is higher than for inland Australia and the annual average solar radiation in northern Australia is higher than for southern Australia [66]. VRE generation plant performance will improve as the quality of these renewable resources increases, in terms of wind speed or solar irradiation leading to lower LCOE results. Therefore, by considering the regional specific characteristics, the accuracy of LCOE calculation can be improved. In Ref. [13], the location-specific PV outputs due to varying strengths of the sun have been considered. The solar electricity yield is calculated in different countries based on population-weighted values which not only consider the solar resource but also the population distribution of the country [13]. In tradition methods, annual energy production is equal to rated power times capacity factor times 8760 h. In Ref. [12], the energy production calculation method is upgraded which considers the turbine diameter, power coefficient and regional power curve [12].

Reliability is the other factor that can impact the plant performance. A reliable power plant with low failure rate has high annual energy production. The annual failure rate of export cables, substations, inter-array cables, moorings and foundations are considered in an ocean energy LCOE calculation [67]. The case study demonstrates that the investment in improved component reliability of a floating wave energy array can reduce the variability and the value of LCOE [67]. Furthermore, with the increasing penetration of VRE, the curtailment of VRE plant can be more frequently used to balance the power supply and demand. For example in China, the curtailment rate for wind power is 15% based on the statistical information by National Energy Administration [39]. The curtailment of VRE can decrease the annual energy production and increase the LCOE correspondingly. The curtailment rate is added in the LCOE equation in Ref. [39] in which the lost power generation is counted.

4.4. Uncertainty and risk-related cost

4.4.1. Scenario-based method

A scenario-based method has been implemented in Ref. [6,7,34] and several scenarios have been considered in their LCOE calculations as shown below [6,7]:

- A conventional scenario that disregards the costs from environmental externalities
- As above but includes environmental externalities
- includes environmental externalities and considers restrictions on where one might be able to site specific technologies
- disregards the costs from environmental externalities but includes restrictions on siting
- high and low natural gas prices
- high and low CO_2 prices
- low solar capital costs
- a location maximum available onshore wind capacity factor

Although the scenario-based method considers the uncertainty of input and policy, it cannot cover all future scenarios.

4.4.2. Sensitivity analysis

The sensitivity analysis method is commonly used in LCOE studies to address project risk [16,29,30,35–39]. The sensitivity method could investigate the impact of input parameters on the output by switching the values of input factors [16]. For example, in Refs. [39], the capacity factor, discount rate and curtailment rates are considered in the sensitivity analysis. In Ref. [35], the authors concluded that the LCOE is very sensitive to module efficiency. The sensitivity of both cost and variation management capacity are analysed in Ref. [29].

Although the sensitivity analysis considers uncertainties in input parameters, it does not take into account the probabilities of the inputs and the endogenous of inputs [16].

4.4.3. Monte Carlo approach

Researchers have applied the Monte Carlo approach to solve the uncertainties in LCOEs [2,11,16,37,40–42]. For example in Refs. [11], the inputs of wind capital cost and capacity factor are set as normal distributions while fixed O&M cost, and variable O&M cost are assumed to follow triangular distribution and log normal distributions, respectively. In Refs. [16], Monte Carlo simulation results show that the LCOE outputs are affected by the correlation between inputs and by controlling for endogeneity, the difference in the mean LCOE can be observed.

The Monte Carlo approach could identify the most influential input parameter [2,40]. Moreover, the LCOE cost of different technologies can be compared and the probability of one type of generation being lower in cost than the other can be determined [11]. The Monte Carlo method provides risk and uncertainty information and the LCOE distribution could help decision makers to evaluate the investment risk on the technology [11].

The flow chart of LCOE calculation using the Monte Carlo method is shown in Fig. 3. The first step is to define the stochastic variables and collect historical data and then create probabilistic density functions based on historical data. Next, M random set of variables are generated and every set of variables could store a LCOE value. Finally, the LCOE distribution can be gathered. After all M scenarios are calculated and the risk can be assessed based on the LCOE distribution.

Although Monte Carlo simulation could solve the uncertainty issues and could provide information for risk analysis, it is not suitable for emerging technologies such as ocean energy as there is a lack of historical data to generate the probability density function.

4.4.4. Market volatility

In a traditional LCOE calculation, the market is assumed to be constant which does not occur in reality. Hence researchers have undertaken studies to consider the price volatility in LCOE calculations. For example, in Ref. [3], a multiplicative correction factor has been proposed to adjust the traditional LCOE to a renewable LCOE calculation where the proposed coefficient captures the synergies of electricity generation and market price. The intermittency and market price are considered in this LCOE model. Energy price adjusted LCOE has been proposed in Refs. [16] based on the continuous energy price rise rates.

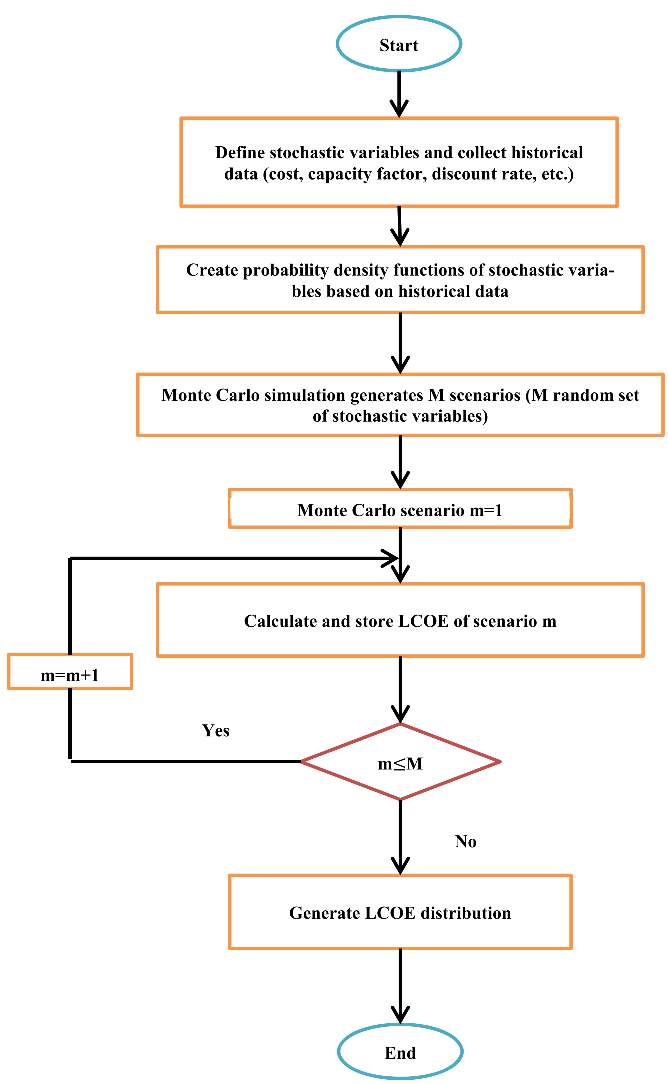

Fig. 3. Flow chart of LCOE calculation using Monte Carlo method.

Furthermore, the electricity price and LCOE are compared in Ref. [4] to assess the performance of market. Moreover, price duration curve and revenue duration curve are collected and compared with a LCOE curve in order to assess the relationship between potential revenue and operating costs. Once the revenue duration curve exceeds the LCOE at any point, then there may be an opportunity for a generator for that technology to fully recover its costs [4].

4.4.5. Policy

In 2015, in order to mitigate climate change the Paris Agreement has been adopted, aiming to limit the increase of global average temperature to well below 2 °C and pursuing efforts to limit it to 1.5 °C [68,69]. In order to achieve these goals, CO_2 emissions should be reduced and governments need to stimulate investment in renewable energy. Several policies have been made to achieve the Paris Agreement goals. Policies have been considered in recent LCOE calculations [5,13,36,43–47]. On the other hand, the calculation of LCOE could assist policy makers and system planners in making cost-effective policies and decisions [60]. The following lists three major types of policy options that have been included in LCOE calculations:

5. Subsidies

Due to the high cost of VRE power plant, subsidies mostly from government, are paid to the VRE plants' owners to make VRE power plant competitive and decrease the carbon emission correspondingly. There are three types of subsidies discussed in the literature including feed in tariff, tax credit and benefits from government.

- Feed in tariff [39,44,45].

Feed in tariff is a globally used policy mechanism for subsidizing renewable energy [44]. The feed in tariff can be different for different types of technologies, different countries and years. In Refs. [44], feed in tariff is considered in LCOE calculation. The authors found that where necessary subsidies can counter the high cost issues of renewable energy in the short term and that the current feed in tariff is not enough for a higher discount rate [44].

- Tax credit [13,44].

Tax credit is usually applied to renewable energy projects to make renewable energy more competitive. Tax credit is considered in Ref. [45] and in this case the tax credit scheme is shown to be more profitable than a feed in tariff.

- Incentive policies [5].

Similar to other subsidies, incentive policies such as zero land cost for the VRE power plant can also increase the investment on renewable energy. In Ref. [5], the impact of preferential loans, zero land cost and tax support on concentrated solar power projects' (CSP) LCOE are analysed. Case studies prove that the combination of the above incentive policies can decrease CSP LCOE result almost 20% and that a preferential loan strategy is the most useful incentive policy in this case [5].

6. Carbon policy

Carbon policies are designed to control carbon emissions. In the power sector implementation of a carbon policy can reduce the production of coal fired power plants and increase the generation of renewable power. There are two major types of carbon policy discussed in the literature as follows.

- Clean Development Mechanism (CDM) [39,46].

The CDM is defined in the kyoto Protocol in which emission reduction projects can sell their certified emission reduction (CER) units in the carbon market [70]. This CDM can be coordinated with LCOE calculation so that the investors of VRE can obtain emission reduction revenue in the carbon market and this can offset generation operational costs and reduce the LCOE correspondingly [39]. A case study in China [39] demonstrates that the LCOE can be reduced by selling CERs in a carbon market and this policy can help achieve grid parity. When an assessment includes the CDM, a low carbon technology will be more competitive [46].

- Carbon price [2,34,36,39].

With the policy of carbon price a financial cost is imposed on companies that generate carbon emissions. In Ref. [2], the equivalent lifetime carbon emission for different types of generation are formulated in LCOE calculation using carbon pricing. This case study shows that the LCOE of all types of generation increases with carbon pricing even for renewable energy. In particular it is found that the LCOE of solar PV increases more rapidly than wind [2].

7. Power purchase agreement (PPA)

PPAs are performance contracts that establish a risk control agreement between the utility and the generator [43]. A PPA allocates the risk between seller and buyer, and addresses energy delivery limits [43]. The energy delivery limits are considered in PPA-based LCOE estimates, which can help vendors reduce their risks and increase profitability.

7.1. Future LCOE projection method

The projections of future LCOE values are difficult as there are uncertainties in cost, performance, discount rate, etc. In the literature, learning curves have been applied in LCOE calculations [5,34,36,39,63,71]. The learning curves show the reduction trend of the technology cost with the cumulative production of that technology [48]. The learning curve and the learning rate can be observed once the technology begins to produce and be installed [48]. However, there is no historical learning rate for emerging technologies and the learning rates of previously emerging technologies can be used as reference [48]. In Ref. [72], a modified learning rate has been calculated for marine energy based on a technology readiness level which could indicate the development stage of technologies.

Learning curves are a useful indicator of future costs [73]. They provide a method for calculating technology cost at different development stages. They can also provide a projection of the future global generation mix when it is embedded in a modeling framework [34].

7.2. Other methods

The authors consider the reliability of data in LCOE calculation in Ref. [74] and propose a new methodology for developing LCOE data that manages the unreliability of "public domain" data by offering a robust method to assess data and trends in generation costs.

In [42], a stochastic LCOE theory has been proposed that could estimate the trade-off between cost and uncertainty on risk. Standard deviation and CVaR deviation are compared to measure LCOE risk and select an optimal portfolio. The general variation in assumptions is examined to find which input has the most influence on LCOE in Refs. [48]. The data assumptions and methodology of five key LCOE studies from the Electric Power Research Institute (EPRI) [75], ACIL Tasman [76], the United States Department of Energy [77], the International Energy Agency [78] and CSIRO [79] have been compared [48]. As the input data and assumptions of different studies and institutions are different, in order to compare the data and LCOE calculation methodologies among five studies on a common basis, aharmonised method is proposed by using a single methodology and averaging for the non-technology assumptions [48]. The proposed method is done in three ways: firstly, exam the effect of the assumption data on LCOE in different reports; secondly, examine the general variation in assumptions and find the assumptions that have the most influence on LCOE; and finally highlight the assumptions which have large variations across the reports [48].

8. LCOE reduction methodologies

Researchers, engineers and policy makers are striving to reduce the LCOE of renewable energy to make renewable energy projects more competitive in the electricity market. There are two approaches, based on the LCOE equation, for reducing the LCOE including total cost reduction and increasing energy production. These methods are summarized in this section.

Targets for cost reduction can be classified as the capital cost, O&M cost, and additional cost. Capital cost reduction and O&M cost reduction can be achieved by the development of the technology. As the technology matures the cost may decrease. Progression to a technology development level is usually simulated by the learning rate. The experience manufacturers and operators gain when developing a technology leads to improvements in manufacturing and the optimization of operational methods both of which contribute to reducing the LCOE in the future [10,36,80]. Increasing the project scale can also reduce the LCOE. The case study in Ref. [2] indicates that the capital costs of emerging renewable energy systems tend to decrease as the nameplate capacity increases provided it is well matched to the energy resource capacity [81]. By increasing the renewable energy project size, the cost per unit reduces due to economies of scale [80]. The development of the industrial supply chain for the renewable technology can potentially reduce the cost as well. The manufacturing processes of supply chain can be repeated and optimized and it is possible to standardise production through assembly lines or automation, hence the cost can be reduced [2,80]. For example, in Ref. [80] the LCOE of tidal stream are assumed to reduce nearly 50% once the cumulative installed capacity reach 2 GW. Low-carbon policies as discussed in Section 4.4.5 are the most common method to reduce cost for the renewable energy project. Subsidies including feed in tariff [39,44,45], tax credit [13,44] and incentive policies [5] can reduce the cost directly or indirectly. For example, in Ref. [44], the additional feed in tariff are calculated for the renewable energy plants to be profitable. Renewable energy projects under CDM [39,46] can offset the total cost by selling their CER units in carbon market. Other indirect subsidies such as research funding, low-cost provision of infrastructure, etc. can help to reduce LCOE [82,83].

The second approach for reducing LCOE by increasing the energy production is more complex. The average capacity factor of the power plant is usually used to calculate the energy production, hence the energy production can be increased by increasing the capacity factor. The methods for increasing the average capacity factor include: innovation in generation structure such as increasing turbine efficiency or decreasing the outage rate, optimization of renewable resources and turbine layout design, and increasing transmission line capacity. Moreover, the VRE farm operators can forecast maintenance with more historical data (operating data and weather data). Hence, the O&M cost could decrease by developing a proactive O&M strategy and maximises turbine operating time [80]. In Ref. [84], the efficiency of wind farms can be improved by optimizing the layout design and blade design hence decrease LCOE. The wake effect of wind or tidal turbines can be minimized by optimizing the layout design hence increase energy production. In real cases, some renewable energy projects cannot operate at their full scale due to transmission constraints. Therefore, proper transmission capacity can also increase the renewable project energy production and reduce LCOE correspondingly. A key factor in reducing capacity factor in VRE LCOE is to ensure that the design rated capacity is not excessive, it should be well matched to the available energy resource

Table 2
Outline LCOE study from academic papers.

Generation type	LCOE range (A $/kWh)	Input	Contribution	ref
Solar PV	0.424–1.528	Discount rate; System cost; System life; Degradation rate; Energy output	1. Summary of PV LCOE, and the input assumptions 2. Grid parity is considered	[30]
	0.556–1.334	Discount rate; Conversion efficiency; System degradation; Solar insolation; Fixed O&M; tax	1. Uncertainty issues are solved 2. LCOE distribution are calculated based on Monte Carlo simulation	[85]
Offshore wind	0.083–0.108	Capital cost, O&M, discount rate, inflation	1. Review the cost of energy metrics 2. Consider the uncertainty in discount rate, inflation rate and future cost. 3. Probabilistic method	[51]
Wind Solar Solar thermal	0.088 (expected value) 0.180 (expected value) 0.269 (expected value)	Capital cost, interest rate, loan period O&M, capacity factor	1. Monte Carlo analysis is applied to solve uncertainty; provide information about risk; 2. LCOE results report as a quantitative distribution 3. Location adjusted LCOE is analysed which could determine how favorable a location is for that technology 4. Evaluate the investment risk on certain technology for decision makers based on the LCOE distribution	[11]
Onshore wind Offshore wind Solar PV Concentrated Solar power (CSP) Biomass combustion geothermal	0.137–0.265 0.209–0.296 0.169–0.376 0.245–0.405 0.194–0.351 0.101–0.448	Capital cost, discount rate, installation lifetime, annuity, load factor, O&M	1. Cost and LCOE comparison of different sources of energy 2. LCOE for geothermal are calculated 3. The cost of using geothermal to generate electricity is attractive.	[52]
Tidal	0.268–1.179	Capital cost, O&M, tidal harmonics, tidal turbine parameters, water depth	1. LCOE mapping spatial and temporal analysis 2. Obtain the geographically distributed costs in a region	[12]
Wind Solar PV Biomass	0.099–0.174 0.172–0.378 0.123–0.154	Capital cost, O&M, tax, decommissioning cost, residual value, lifespan, discount rate, capacity factor, feed in tariffs	1. Required subsidies for renewable energy are calculated 2. Propose policy recommendations (electricity price reform)	[44]
Offshore wind Tidal Wave	0.233 0.269 0.459	Capital cost, decommissioning cost, capacity factor, discount rate, O&M cost	1. Calculate LCOE for marine energy 2. The benefits of combined marine devices are analysed	[53]
Solar PV Solar thermal Onshore wind Offshore wind Hydropower biomass geothermal wave Tidal	Mean: 0.199 0.871 (With carbon price) Mean: 0.452 1.537 (With carbon price) Mean: 0.115 0.191 (With carbon price) Mean: 0.258 0.417 (With carbon price) Mean: 0.109 0.777 (With carbon price) Mean: 0.144 0.658 (With carbon price) Mean: 0.098 0.360 (With carbon price) Mean: 0.562 1.483 (With carbon price) Mean: 0.479 1.277 (With carbon price)	Capital cost, O&M cost, system lifetime, capacity factor, lifecycle greenhouse gas emission	1. Calculate LCOE consider the uncertainty and variability of input variables 2. Monte Carlo approach 3. Carbon pricing, life-cycle carbon are assessed 4. The future potential LCOE reduction method	[2]
Onshore wind Offshore wind PV wave	0.231 0.254 0.144 0.481	Capital cost, O&M cost, capacity factor, discount rate, degradation rate, life of the system	1. Calculate LCOE based on local characteristics including local renewable resource potential and island specific costs. 2. Combine renewable technologies could achieve renewable energy target while reduce electricity rates. 3. Capacity factor have the highest impact on	[60]

(*continued on next page*)

Table 2 (*continued*)

Generation type	LCOE range (A $/kWh)	Input	Contribution	ref
			LCOE compared to other inputs based on sensitivity analysis.	
PV CSP	0.258–0.602 0.201–0.430	Capital cost, balance of system cost, O&M, insurance cost, learning rates, cumulative installed capacity, electricity production, degradation factor, discount rate, lifetime	1. Learning curves are considered in LCOE model 2. LCOE future evaluation: Continuous LCOE results from 2010 to 2050 3. When to reach grid parities of different technologies and scenarios.	[36]
CSP	0.309	Capital cost, O&M, annual energy production, discount rate, tax, construction period, learning rate, incentive policies, insurance cost	1. Establish a lifetime cost for CSP projects. 2. The incentive policies such as tax support are included in LCOE calculation.	[5]
PV	0.070–0.278	System installation cost, solar insolation, economic life, the losses of system, module cost, module efficiency, system balancing cost, inflation rate, discount rate	1. Quantitatively investigate the LCOE of large-scale PV system. 2. Use 3D contour plots to assess the impact of parameters on LCOE	[38]
High concentrator PV	0.050–0.163	Capital cost, O&M, income tax rate, tax depreciation, annual degradation rate, lifetime, discount rate, annual inflation rate	1. LCOE of high concentrator PV is calculated 2. Spatially-distributed LCOE are calculated	[86]
Wind	0.0735	Capital cost, O&M, curtailment rate, carbon price, carbon reduction from projects, learning curve	1. A learning curve based LCOE is proposed 2. The effect of carbon pricing on grid-parity is assessed 3. Carbon price and carbon emission trading scheme are considered.	[39]
Wind Hydro Biomass Solar Tidal & Geothermal	0.166 (mean value) 0.137 (with CER) 0.076 (mean value), 0.047 (with CER) 0.172 (mean value), 0.117 (with CER) 0.510 (mean value), 0.470 (with CER) 0.164 (mean value), 0.140 (with CER)	Investment, O&M, lifetime, cost of issuing Certified Emissions Reduction credits (CER), CER issuance cost, discount factor, length of emission reduction crediting period, degradation of generation, location	1. Calculate LCOE with and without Clean Development Mechanism (CDM); 2. CDM makes renewable energy more competitive 3. CER price, cost of CER insurance, length of crediting period are in the new LCOE equation	[46]
Wind	0.045–0.158	Capital cost, O&M, wind speed, lifetime, capacity factor, discount rate	1. Calculate wind LCOE on the Caribbean island of Trinidad and Tobago 2. Technical and economic assessments of wind farms are conducted	[87]

capacity [81].

9. Comparison of research

Table 2 compares LCOE studies from the academic literature and Table 3 summarizes the LCOE studies from technical reports. The LCOE range for different types of renewable energy technologies, input parameters and major contributions are listed in Tables 2 and 3 below. The LCOE range is converted to AUD/kWh of year 2019.

Table 2 summarizes the VRE LCOE calculation in academic papers. Almost all the studies consider capital cost, O&M cost, lifetime, capacity factor and discount rate in LCOE calculation. LCOE calculation is upgraded in these studies to increase the accuracy of VRE LCOE calculation in different aspects. To be more specific, the degradation rate of solar PV system are considered in Refs. [30,85]. For example, the degradation rate of solar PV system is set as 0.5% per year [30]. The input uncertainties are resolved in Ref. [2,11,51,60,85] using probabilistic methods as discussed in Section 4.4.3. Policies including feed in tariffs, incentive policies, carbon pricing and CDM are analysed in LCOE calculation [2,5,39,44,46] as discussed in Section 4.4.5. Spatially-distributed LCOE are calculated in Ref. [12,86].

The assumptions and LCOE equation may vary greatly across a range of studies, therefore the LCOE results for same technology may have significantly different results. The LCOE range of onshore wind, offshore wind, solar, solar thermal, biomass, tidal and wave are summarized and converted to 2019 Australian dollars in Fig. 4. Where it is clearly evident that onshore wind, solar and biomass are more competitive than other technologies.

Table 3 summarizes the VRE LCOE calculation in techical reports. The reports focus more on real projects and future LCOE projections. For example, in Ref. [72] a technology readiness level is applied in a future LCOE projection while learning rate is used in Ref. [89] for future LCOE projection. The LCOE range of onshore wind, offshore wind, solar, solar thermal, biomass, tidal and wave in the technical reports are summarized and converted to 2019 Australian dollars in Fig. 5. The results are similar to the results in Fig. 4 where onshore wind and solar are more mature and with a lower LCOE level whereas wave and tidal energy have higher LCOE levels as well as higher LCOE ranges, as they are emerging technologies.

10. Conclusion, future research directions and recommendations

This paper reviews the LCOE methodology and data found in existing studies and indicates the improvements that can be made to the traditional LCOE method when calculating a VRE LCOE, including investment-related cost, operational-related cost, plant performance and the uncertainty and risk-related costs. Moreover, the review summarizes the LCOE range and contributions in existing studies. Overall, there is a lack of a standard methodology for calculating the LCOE for VRE and the future research could focus on the following aspects:

For academics, future VRE LCOE study can investigate the impact of turbines' layout on LCOE results. For example, the wake effect of wind and tidal farms can change the energy production which could influence the LCOE results. The reliability and stability of the grid is another topic that should be considered in VRE LCOE calculations as the large penetration of VRE may challenge power grid and cause additional costs on grid such as ramping and reserve costs. The endogeneity of LCOE input parameters has not yet been fully studied and could be accounted for by using a mathematical model or data-driven method. The fluctuations of electricity price can also be involved in LCOE calculation to account for changes in the energy production pattern and operation cost.

System planners might focus more on the impacts of new VRE plants on the power grid. An LCOE based on a combination of different VRE

Table 3
Outline LCOE study from technical report.

Technology	LCOE range (A $/kWh)	Inputs	Key findings	Ref
hydropower Onshore wind Bioenergy and geothermal Solar PV Offshore wind CSP	0.070 0.085 0.099 0.141 0.197 0.310	Capital cost, O&M, capacity factor, life span	1. LCOE of large-scale solar PV has fallen significantly to $0.10/kWh in 2017. 2. The renewable generation cost will continue to reduce through 2020 and beyond. 3. The reduction of installed costs lead to the fallen of LCOE, especially in onshore wind and solar PV. 4. The improvement of technology, competitive procurement and large base of experienced project developers are three key potential cost reduction drivers.	[9]
Wave Tidal (commercial scale) Ocean thermal energy conversion (OTEC)	0.174–0.382 0.173–0.289 (projected value) 0.173–0.75	Capital cost, O&M, capacity, discount rate, lifetime, availability	1. A technology readiness level is applied in future LCOE projection which indicates the commercial ability of a technology 2. The cost reduction trajectories of ocean technologies including wave, tidal and OTEC are calculated. 3. The establishment of early arrays for tidal and wave energy could lead to the reduction of LCOE. It is important to gain the confidence in emerging technology at early stages. 4. OTEC can generate electricity and desalination simultaneously which could impact LCOE as external factor	[72]
Coal with CCS Gas with CCS Solar thermal biomass Wind Solar	0.150–0.220 (project value in 2050) 0.110–0.200 (project value in 2050) 0.090–0.110 (project value in 2050) 0.250–0.370 (project value in 2050) 0.040–0.100 (project value in 2050) 0.030–0.060 (project value in 2050)	Carbon price, risk premium, different categories.	Limitations in existing LCOE 1. LCOE are applied to certain technologies with their own characteristics which cannot provide all electricity supply. 2. For low variable renewable uptake regions, the current system has the ability to absorb VRE using balancing capacity. However, with the share of variable renewable rise, the system needs more balancing capacity to satisfy system reliability criteria. 3. It is difficult to compare the technologies with different climate policy risks.	[47]
Solar	0.098–0.133	CAPEX, OPEX, discount rate, lifetime, capacity factor, marginal and distribution loss factors, degradation	1. The LCOE of Twelve ARENA-supported large-scale solar projects in Australia are analysed and compared 2. The capacity factors of solar projects are calculated based on the combination of degradation, availability and marginal and distribution loss factors (MLF).	[88]
Tidal	0.573	CAPEX, OPEX, lifetime, capacity factor	1. After 2040, there are at least 4 metric tons of carbon dioxide per year reduction by the installation of ocean renewable energy. 2. Tidal energy are possible to achieve £80 per MWh by 2 GW installed. 3. The ocean renewable energy are expected to have significant cost reductions as the industry are transit from pre-commercial arrays to commercial projects.	[80]
PV Wind onshore Offshore wind	0.088–0.321 0.058–0.321 0.146–0.467	CAPEX, OPEX, lifetime, electricity produced, decommissioning and waste management costs, carbon costs, discount rate	1. The full cost accounting is important during energy transitions. 2. There are three categories in full cost of electricity, plant level cost, electricity system level cost and external or social cost 3. The largest non-internal costs include the air pollution, climate change risks and system costs.	[8]
Wind onshore Offshore wind Solar Biomass CHP Dedicated biomass Tidal stream Wave Geothermal CHP Hydro	0.089–0.146 (project value in 2030) 0.178–0.229 (project value in 2030) 0.093–0.128 (project value in 2030) 0.284–0.379 (project value in 2030) 0.172–0.203 (project value in 2030) 0.351–0.756 (project value in 2030) 0.328–0.694 (project value in 2030) −0.008–0.452 (project value in 2030) 0.107–0.182 (project value in 2030)	Development cost of a project, capital, o&m, heat revenue for CHP, availability, load factor, Pre-development, construction, operation time periods	1. This study provided an independent assessment method of LCOE calculation. 2. The LCOE ranges for different technologies are calculated with different project cost. 3. The future costs are projected using a learning rate and the changing of future LCOE are assessed.	[89]
PV Solar thermal geothermal Wind onshore Wind offshore	0.053–0.067 0.143–0.264 0.104–0.162 0.042–0.082 0.091–0.177	Capacity factor, Capex, O&M, debt, depreciation, interest, tax, lifetime, construction time	1. Subsidies are considered in LCOE comparison of different generation technologies. 2. Illustration of the historical LCOE declines for wind and utility-scale solar technologies. The historical LCOE data for wind and solar are illustrated.	[90]

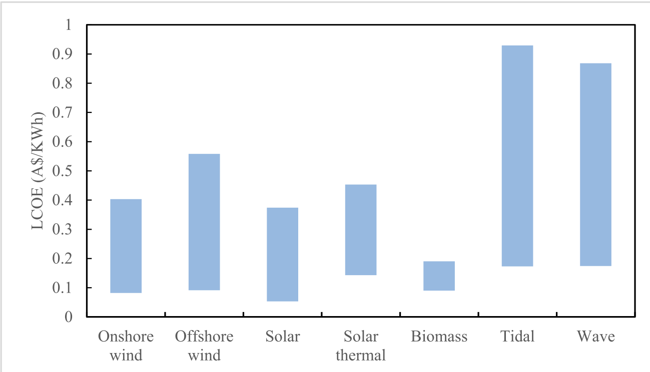

Fig. 4. LCOE range for VRE in academic paper.

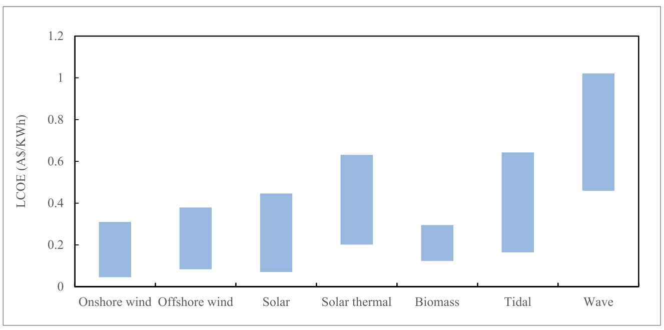

Fig. 5. LCOE range for VRE in technical reports.

modalities can be investigated as the total power output of different types of VRE and may have less fluctuation and less influence on grid. The changing of system technology can lead to the change of plants' energy production and operation costs. Therefore, the impacts of the changing of system topology such as retirement of aging coal, gas units and transmission expansion on VRE LCOE results can be studied. Comparing and calculating the VRE LCOE with different grid support options, including different types of energy storage, demand response, virtual power plant, etc. can be very useful for system planners to make future planning decisions. The characteristics of different types of renewable generation should be considered. For example, tidal is more predictable than solar and wind, which means it has less risk after installation and may support power grid in extreme conditions. Moreover, risks such as renewable forecast errors and extreme events can have significant impacts on a power grid and it can also be considered in LCOE calculation.

LCOE calculation can help policy makers to make and compare renewable policies. The policies for VRE on electricity markets can be tested to increase revenue. Levelized revenue of VRE can be calculated and compared with LCOE. Technologies with high LCOE can also be competitive if they have higher levelized revenue of electricity.

Finally, we propose some recommendations for practical steps to improve VRE LCOE calculations. First, the intermittent characteristic of VRE needs to be addressed carefully in LCOE calculation. The energy production needs to consider regional and seasonal performance. The plants' energy production should include electricity system operation simulation as well as the grid balancing cost. It can be significantly more accurate to include a consideration of the whole electricity system operation than to just calculate an average capacity factor. Second, regional specific cost should be considered, as the installation cost and operation cost can be significantly different for capital cities and rural areas. Therefore, regional cost factors can be defined to correct the cost difference based on statistical methods. Third, the uncertainties of inputs should be carefully assessed and it is likely that probabilistic methods will demonstrate more competitive values of VRE LCOE than the deterministic methods for those technologies that have historical operation and costs data. Last but not least, renewable energy policies cannot be ignored, as these policies can play an important role in energy transformation and VRE LCOE can be reduced with proper policies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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